

HYDROGEN STORAGE COMPOSITIONS AND METHODS OF MANUFACTURE THEREOF

BACKGROUND

[0001] This disclosure is related to hydrogen storage compositions and methods of manufacture thereof.

[0002] Hydrogen is a "clean fuel" because it can be reacted with oxygen in hydrogen-consuming devices, such as a fuel cell or a combustion engine, to produce energy and water. Virtually no other reaction byproducts are produced in the exhaust. As a result, the use of hydrogen as a fuel effectively solves many environmental problems associated with the use of petroleum based fuels. Safe and efficient storage of hydrogen gas is, however, essential for many applications that can use hydrogen. In particular, minimizing volume and weight of the hydrogen storage systems are important factors in mobile applications.

[0003] Several methods of storing hydrogen are currently used but these are either inadequate or impractical for wide-spread mobile consumer applications. For example, hydrogen can be stored in liquid form at very low temperatures. However, the energy consumed in liquefying hydrogen gas is about 40% of the energy available from the resulting hydrogen. In addition, a standard tank filled with liquid hydrogen will become empty in about a week through evaporation; thus dormancy is also a problem. These factors make liquid hydrogen impractical for most consumer applications.

[0004] An alternative is to store hydrogen under high pressure in cylinders. However, a 100 pound steel cylinder can only store about one pound of hydrogen at about 2200 psi, which translates into 1% by weight of hydrogen storage. More expensive composite cylinders with special compressors can store hydrogen at higher pressures of about 4,500 psi to achieve a more favorable storage ratio of about 4% by weight. Although even higher pressures are possible, safety factors and the high

amount of energy consumed in achieving such high pressures have compelled a search for alternative hydrogen storage technologies that are both safe and efficient.

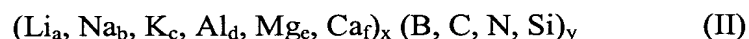
[0005] In view of the above, there is a need for safer, more effective methods of storing and recovering hydrogen. In addition, there is a desire to minimize the overall system volume and weight.

BRIEF DESCRIPTION OF THE INVENTION

[0006] Disclosed herein is a method for making a combinatorial library comprising disposing on a substrate comprising silicon, silicon nitride, silicon carbide or silicon boride at least one reactant, wherein the reactants are lithium, magnesium, sodium, potassium, calcium, aluminum or a combination comprising at least one of the foregoing reactants; heat treating the substrate to create a diffusion multiple having at least two phases; contacting the diffusion multiple with hydrogen; detecting any absorption of hydrogen; and/or detecting any desorption of hydrogen.

[0007] Disclosed herein too is a method of regenerating hydrogen comprising contacting at least one compound selected from the group consisting of AlSi , Ca_2Si , CaSi , CaSi_2 , KSi , K_4Si_{23} , $\text{Li}_{22}\text{Si}_5$, $\text{Li}_{13}\text{Si}_4$, Li_7Si_3 , $\text{Li}_{12}\text{Si}_7$, Mg_2Si , NaSi , NaSi_2 , $\text{Na}_4\text{Si}_{23}$, or a combination comprising at least one of the foregoing compounds in hydrogen to form a hydrogenated compound; and heating the hydrogenated compound to recover the hydrogen.

[0008] Disclosed herein too is a method of regenerating hydrogen comprising contacting a compound with hydrogen to form a hydrogenated compound; wherein the compound has the formula (II)



where Li is lithium, Na is sodium, Mg is magnesium, K is potassium, Ca is calcium, Al is aluminum; B is boron, C is carbon and N is nitrogen, Si is silicon; a, b, c, d, e and f may be the same or different and have values from 0 to 1; and x and y have values of about 1 to about 22; and heating the hydrogenated compound to recover the hydrogen.

[0009] Disclosed herein too is a compound of a diffusion multiple having the formula (II)



where Li is lithium, Na is sodium, Mg is magnesium, K is potassium, Ca is calcium, Al is aluminum; B is boron, C is carbon and N is nitrogen, Si is silicon; a, b, c, d, e and f may be the same or different and have values from 0 to 1; and x and y have values of about 1 to about 22.

[0010] Disclosed herein too is a composition comprising a hydride of a compound, wherein the compound is AlSi, Ca₂Si, CaSi, CaSi₂, KSi, K₄Si₂₃, Li₂₂Si₅, Li₁₃Si₄, Li₇Si₃, Li₁₂Si₇, Mg₂Si, NaSi, NaSi₂, Na₄Si₂₃, or a combination comprising at least one of foregoing compounds.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] Figure 1 is a schematic showing the arrangement of a diffusion multiple assembly in an silicon substrate;

[0012] Figure 2 is a schematic showing how the diffusion multiple assembly is sliced for purposes of analysis;

[0013] Figure 3 is a schematic showing a system for the generation of hydrogen from the hydrides of light metal silicides, borosilicides, carborosilicides and nitrosilicides.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0014] Disclosed herein is a method for developing a combinatorial library to determine silicides, borosilicides, carborosilicides and nitrosilicides that may be advantageously used for the storage of hydrogen. Disclosed herein too are methods for manufacturing silicides, borosilicides, carborosilicides and nitrosilicides that can be subsequently hydrogenated to efficiently store hydrogen. Disclosed herein too are compositions comprising silicides, borosilicides, carborosilicides and nitrosilicides that can store hydrogen for use in the generation of energy in fuel cell applications for

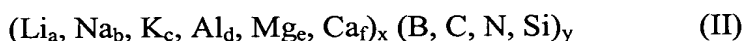
automobiles, homes and apartments, manufacturing industries, and the like. The aforementioned method for developing a combinatorial library to determine silicides, borosilicides, carbosilicides and nitrosilicides that may be used for the storage of hydrogen advantageously permits the simultaneous large scale testing of a wide variety of materials. This high efficiency methodology facilitates the creation of a large number of controlled compositional variations in bulk samples for fast and systematic surveys of bulk properties of the silicides, borosilicides, carbosilicides and nitrosilicides. These combinatorial libraries when used in conjunction with microanalytical techniques such as electron probe microanalysis, electron backscatter diffraction analysis, and the like, can be additionally used for efficient surveys of phase equilibria, coefficients, precipitation kinetics, properties and composition-phase-property relationships for accelerated design of multi-component alloys and systems.

[0015] Complex hydrides from which hydrogen can be obtained generally consist of a H-M complex, where M is a metal and H is hydrogen. Such hydrides may have ionic, covalent, metallic bonding or bonding comprising a combination of at least one of the foregoing types of bonding. These hydrides preferably have a hydrogen to metal ratio of greater than or equal to about 1. The reaction between a metal and hydrogen to form a hydride is generally a reversible reaction and takes place according to the following equation (I):



Complex hydrides can store up to about 18 weight percent (wt%) of hydrogen, and have high volumetric storage densities. The volumetric storage density of hydrides is greater than either liquid or solid hydrogen, which makes them very useful in energy storage applications. The process of hydrogen adsorption, absorption or chemisorption results in hydrogen storage and is hereinafter, for the sake of simplicity, referred to as absorption, while the process of desorption results in the release of hydrogen.

[0016] In an exemplary embodiment, compositions comprising light metal silicides, borosilicides, carbosilicides and nitrosilicides can form hydrides that may be reversibly decomposed at relatively low temperatures of less than or equal to about 300°C to release hydrogen. The light metals are alkali metals and/or alkaline earth metals. Preferred light metals are lithium, sodium, magnesium, potassium, aluminum and calcium. The silicides, borosilicides, carbosilicides and nitrosilicides have the formula (II)



where Li is lithium, Na is sodium, Mg is magnesium, K is potassium, Ca is calcium, Al is aluminum; B is boron, C is carbon and N is nitrogen, Si is silicon; a, b, c, d, e and f may be the same or different and have values from 0 to 1; and x and y have values of about 1 to about 22. The sum of a+b+c+d+e+f is preferably equal to 1.

[0017] In one embodiment, a method of developing a combinatorial library for determining the hydrogen storage capabilities of a silicides, borosilicides, carbosilicides and nitrosilicides is via the use of a diffusion multiple. A diffusion multiple is a compound that is the product of an interdiffusion reaction formed between a first reactant and a second reactant when both reactants are placed in closed proximity with each other and heated to a temperature effective to permit interdiffusion to take place. The temperature effective to permit the interdiffusion is one that can overcome the activation energy of diffusion and achieve at least a degree of interdiffusion of the reactants within a manageable time. Such a temperature is generally about 200 to about 2000°C, depending upon the reactants.

[0018] Diffusion multiples are generally manufactured or prepared by placing reactants in a substrate to form a diffusion multiple assembly; optionally subjecting the diffusion multiple assembly to hot isostatic pressing; heat treating the diffusion multiple assembly to promote interdiffusion of the reactants with one another and/or interdiffusion between the reactants with the substrate; optionally cutting, polishing and grinding the diffusion multiple; identifying the elemental composition of the various phases present in the diffusion multiple; and charging the diffusion multiple

with hydrogen by contacting it with a hydrogen rich gaseous mixture and determining the phases that absorb hydrogen.

[0019] In one exemplary method of making a diffusion multiple assembly comprising light metal silicides, borosilicides, carbosilicides and nitrosilicides, the diffusion multiple is prepared by drilling holes into an silicon, silicon boride (SiB_4), a silicon carbide (SiC) or a silicon nitride (Si_3N_4) block/substrate. These holes generally end half-way through the thickness of the block. Some holes are spaced apart from one another such that during the heat treatment, there is only one reactant reacting with the substrate material to form binary couples and binary solid solutions. When the substrate comprises silicon boride, silicon carbide or silicon nitride, ternary triples may be formed. In another manner of making a ternary triple, holes are spaced in close proximity in pairs with each other as shown in the Figure 1. This arrangement, i.e., where the holes are spaced in close proximity in pairs may be used to generate ternary diffusion triples (also termed ternary compounds and/or ternary solid solutions) upon subjecting the diffusion multiple assembly to heat treatment. The reactants are generally placed into the holes in a loose form i.e., they do not need to be a tight fit.

[0020] When the substrate is manufactured from a single element, the number of holes drilled in the substrate is generally equal to the minimum number of diffusion multiples desired. Thus for example, if a binary diffusion couple is desired in a substrate made from a single element such as silicon, one hole is drilled into the substrate, while if a ternary diffusion triple is desired, two holes are drilled into the substrate in close proximity to one another. As stated above, another method of making a ternary triple comprises drilling a single hole into a substrate, wherein the substrate is made up of an alloy. The holes are about 1 to about 10 millimeters in diameter. The preferred diameter is about 5 millimeter. The thickness of the substrate is generally about 5 to about 25 millimeters in diameter. The preferred thickness of the substrate is about 25 millimeters.

[0021] The distance "d" between the holes in the substrate is maintained as close as possible for those drilled in pairs. The distance d is generally about 0.1 to

about 2000 micrometers. Within this range, it is generally desirable to utilize the distance to be less than or equal to about 400, preferably less than or equal to about 200, and more preferably less than or equal to about 100 micrometers.

[0022] In an exemplary embodiment, in one manner of proceeding, a diffusion multiple assembly comprises a silicon substrate as shown in Figure 1. The silicon substrate is used to prepare a combinatorial library from alkali metals and/or alkaline earth metals. In other words, the alkali metals and/or the alkaline earth metals are placed in the holes in the substrate to form the diffusion multiples. The substrate has a diameter of 2.0 inches and the holes containing the reactants are drilled to a depth of 0.5 inch. The reactants selected for placement in the holes in the substrate are potassium, lithium, sodium, magnesium, aluminum and calcium. As may be seen from the Figure 1, the reactants sodium, potassium, lithium and aluminum are placed into individual holes in the substrate. These may be used to prepare binary diffusion couples of the reactants with silicon.

[0023] Ternary diffusion triples of the reactants may also prepared by drilling holes in close proximity to each other as may be seen in Figure 1. The ternary triples comprise lithium and sodium with silicon, lithium and potassium with silicon, sodium and potassium with silicon, lithium and aluminum with silicon, and sodium and aluminum with silicon.

[0024] The operation of placing the light metals into the hole in the substrate is carried out in a well-controlled environment such as a glove box filled with pure argon to prevent the light-elements from oxidation. The amount of light-elements in each hole is usually less than a quarter of the volume of the hole such that there will be no pure light elements left after the interdiffusion/heat treatment step. The silicon block with the light-elements in the holes are then transferred to a furnace or a reactor. The furnace or reactor is either in a vacuum or a protective environment such as argon. The block is then heated to an elevated temperature to allow significant interdiffusion to take place among the elements in the holes and the silicon substrate.

[0025] The block is preferably heat treated from a temperature of about 580 to about 900°C to permit the melting of the reactants or their eutectic compounds. The heat treatment is generally conducted in a convection furnace. The heat treatment to form the diffusion couple may also include using radiant heating and/or conductive heating if desired. The melted reactants diffuse and react with the silicon substrate to form silicides, doped phases, and solid-solution compositions. When silicon carbide is used as the substrate, the heat treatment is generally conducted at temperatures of about 580 to about 1,250°C so that the formation of a diffusion multiple is facilitated within a reasonable time. The preferred temperature for heat treatment is 600°C. When silicon nitride is used as the substrate, the heat treatment is generally conducted at temperatures of about 600 to about 1,250°C so that the formation of a diffusion multiple is facilitated within a reasonable time. The preferred temperature for heat treatment is 600°C. When silicon boride is used as the substrate, the heat treatment is generally conducted at temperatures of about 580 to about 1,250°C so that the formation of a diffusion multiple is facilitated within a reasonable time. The preferred temperature for heat treatment is 600°C.

[0026] The time period of the heat treatment of the diffusion multiple assembly is about 5 to about 100 hours. Within this range, it is generally desirable to heat treat the diffusion multiple assembly for greater than or equal to about 10, preferably greater than or equal to about 15, and more preferably greater than or equal to about 17 hours. Also desirable within this range is a time period of less than or equal to about 75, preferably less than or equal to about 50 and more preferably less than or equal to about 40 hours. An exemplary time period of heat treatment at a temperature of 450°C is about 24 hours.

[0027] After the heat treatment to form the diffusion multiple, a slicing operation may be performed on the diffusion multiple assembly. The slicing step is designed to expose different compounds/solid solutions formed at different locations of the diffusion multiple assembly as shown in Figure 2. The slicing operation is generally performed using mechanical cutting using a saw or wire discharge electro-machining (EDM). Following slicing, the respective slices may be optionally subjected to grinding and polishing if desired. Following the optional grinding and

polishing operation, the samples are subjected to electron microprobe analysis and electron backscatter diffraction (EBSD) analysis to identify the phases and compounds prior to being tested for the ability of the light metal silicides, borosilicides, carbosilicides and nitrosilicides for hydrogenation. The identification of the phases or compounds as defined herein implies locating and/or analyzing the phase or the compound.

[0028] After the electron microprobe and EBSD analysis of the light metal silicides, borosilicides, carbosilicides and nitrosilicides, the resulting diffusion multiples may be converted to hydrides by exposure to hydrogen or upon hydrogenation.

[0029] The following silicides can be obtained from the diffusion multiple assembly shown in Figure 1 and may be used for a determination of hydrogen potential: AlSi , Ca_2Si , CaSi , CaSi_2 , KSi , K_4Si_{23} , $\text{Li}_{22}\text{Si}_5$, $\text{Li}_{13}\text{Si}_4$, Li_7Si_3 , $\text{Li}_{12}\text{Si}_7$, Mg_2Si , NaSi , NaSi_2 , $\text{Na}_4\text{Si}_{23}$, or the like, or a combination comprising at least one of the foregoing silicides. Ternary silicides in general, and ternary silicides comprising the foregoing silicides in particular may be useful for hydrogenation and for generating hydrogen. In addition borosilicides, carbosilicides and nitrosilicides of lithium, magnesium calcium, sodium, potassium and aluminum may also be used for hydrogenation and for generating hydrogen.

[0030] The silicides, borosilicides, carbosilicides and nitrosilicides generally have at least one of potassium, lithium, magnesium or sodium. The presence of the potassium, lithium, magnesium and sodium promotes an affinity for hydrogen. Silicon on the other hand has a low affinity for the hydrogen and this feature is offset by the affinity of hydrogen displayed by potassium, lithium, magnesium and/or sodium. Without being limited to theory it is believed that those elements of the diffusion multiple that have a high affinity for hydrogen generally facilitate absorption of hydrogen, while those elements such as silicon that have a low affinity for hydrogen generally facilitate the desorption.

[0031] The diffusion multiple comprising the light metal silicides, borosilicides, carbosilicides and nitrosilicides can generally be tested for their ability to absorb and desorb hydrogen. The composition gradients formed during the preparation of a diffusion multiple can serve as a combinatorial library to determine which specific composition can absorb and desorb hydrogen.

[0032] The ability of a light metal diffusion multiple to reversibly absorb and desorb hydrogen may be detected by a variety of analytical techniques. In general, the process of absorption of hydrogen into the silicides, borosilicides, carbosilicides and nitrosilicides results in a change in appearance because of a crystal structure change and/or a volumetric expansion. In addition, the absorption of hydrogen into the silicides, borosilicides, carbosilicides and nitrosilicides is generally accompanied by an exotherm, while the desorption of the hydrogen is generally accomplished by the application of heat. The analytical techniques that can be used to measure the changes in the diffusion multiples are time of flight secondary mass ion spectrometry (ToF-SIMS), tungsten oxide (WO_3) coatings and thermography. In addition, the silicides, borosilicides, carbosilicides and nitrosilicides can be screened by observing the diffusion multiple after hydrogenation, since the phases that do undergo hydrogenation (i.e., hydrides) generally become pulverized.

[0033] The ToF-SIMS has the capability to detect the absorption and desorption of all elements including hydrogen, which makes it useful for the determining those compositions present in the light metal diffusion multiple that can readily be used for the storage of hydrogen. This technique can operate at temperatures of about -100 to about 600°C , has a high sensitivity to hydrogen and is therefore a useful tool for investigating the combinatorial libraries generated by the diffusion multiples. The ToF-SIMS can therefore be effectively used to map the absorption temperatures and the reaction conditions during the hydrogenation process.

[0034] The tungsten oxide (WO_3) generally changes its color when it reacts with hydrogen. In order to use the tungsten oxide as a detector for the hydrogen uptake in the various compositions of the diffusion multiple, the diffusion multiple is coated with WO_3 after the hydrogenation reaction. When the diffusion multiple is

heated up to release the hydrogen, the WO_3 changes color as the hydrogen desorbs from the diffusion multiple.

[0035] Thermography or thermal imaging (infrared imaging) may also be used to determine the absorption and desorption of hydrogen. When a phase in the diffusion multiple absorbs hydrogen, the local temperature rises, while when the phase desorbs hydrogen, the local temperature decreases. Thermography can therefore be used to image the compounds that absorb or desorb hydrogen.

[0036] In one embodiment, the silicides, borosilicides, carborosilicides and nitrosilicides can be hydrogenated by subjecting them to a mixture of gases comprising hydrogen. As stated above, the silicides, borosilicides, carborosilicides and nitrosilicides generally release heat during the absorption of hydrogen. The hydrogen may then be released by reducing the pressure and supplying heat to the hydrogenated silicides, borosilicides, carborosilicides and nitrosilicides. The desorption of hydrogen often requires thermal cycles. Such thermal cycles can be obtained by the application of electromagnetic fields or by passing electrical current through the material of interest. This can be accomplished because most hydrogenated silicides, borosilicides, carborosilicides and nitrosilicides are electrically conductive. The resistance of these materials changes with the extent of hydrogen storage.

[0037] In one embodiment, the desorption of stored hydrogen can be facilitated by the use of electromagnetic fields. Microwave energy can be directly applied to the hydrogenated silicides, borosilicides, carborosilicides and nitrosilicides or to a suitable medium such as water, alcohols, or the like, intermixed with the hydrogenated silicides, borosilicides, carborosilicides and nitrosilicides to allow for the local release of hydrogen under controlled conditions, without heating the whole system. This method provides a high efficiency of desorption, which generally occurs at temperatures lower than those achieved due to heating brought about by conduction and/or convection. This phenomena occurs due to a local excitation of the bonds in the silicides, borosilicides, carborosilicides and nitrosilicides by the microwaves. The desorption may be conducted by two different methods. The first of these methods comprises using microwaves to achieve a release of the entire hydrogen content. The

second method comprises using a microwave treatment just to initialize the desorption process which then can be continued by either conductive and/or convective heating at lower temperatures and in a much easier manner than when heated by only conductive and/or convective heat from the start of the process.

[0038] In yet another embodiment, hydrogen desorption can be induced by the heat generated by an electrical resistor embedded in the silicides, borosilicides, carbosilicides and nitrosilicides. The energy of the current flowing into the resistor is converted into heat by the Joule effect. The amount of heat created locally by the current flow is particularly high in the case of a compressed powdered silicide material, with hot spots occurring on the current paths between powder particles, where the resistivity is very high. In extreme cases, powder welding may occur at the hot spots. Therefore, the current parameters should be adjusted properly to avoid sintering or powder welding. Depending on the conditions of the process, the silicides, borosilicides, carbosilicides and nitrosilicides may be heated directly, or by the use of multiple resistors as detailed above.

[0039] In yet another embodiment, hydrogen absorption and desorption is accomplished by mixing fine particles of the silicides, borosilicides, carbosilicides and nitrosilicides with an appropriate amount of another chemical composition that has a higher thermal conductivity to conduct heat faster to the hydrogenated compound for hydrogen release. In yet another embodiment, hydrogen desorption is accomplished by using the exhaust heat released from the proton exchange membrane (PEM) fuel cells to heat up the hydrogenated silicides, borosilicides, carbosilicides and nitrosilicides.

[0040] In yet another embodiment, dopants comprising titanium, vanadium, zirconium, yttrium, lanthanum, nickel, manganese, cobalt, silicon, gallium, germanium, and the elements from the lanthanide series may be added to catalyze the desorption of hydrogen. The dopant may be added in an amount of up to about 20 wt%, of the total hydrogen storage composition prior to the storage of hydrogen. It is generally desirable to add the dopant in an amount of less than or equal to about 15, preferably less than or equal to about 10 and more preferably less than or equal to

about 5 wt% of the total weight of the hydrogen storage composition (i.e., the diffusion multiple) prior to the storage of hydrogen.

[0041] The hydrogen desorbed from these silicides, borosilicides, carborosilicides and nitrosilicides can be about 1 to about 8 wt%, with amounts of greater than or equal to about 4 wt% preferred, amounts of greater than or equal to about 5 wt% more preferred, and amounts of greater than or equal to about 6 wt% even more preferred.

[0042] As stated above, the combinatorial method of determining the capability of light metal silicides, borosilicides, carborosilicides and nitrosilicides to absorb and desorb hydrogen is quick and efficient. The light metal silicides, borosilicides, carborosilicides and nitrosilicides that are determined to absorb and desorb hydrogen may be utilized in fuel cells, gas turbines, and the like for the storage of energy.

[0043] In one exemplary method of producing and storing hydrogen from hydrides of the light metal silicides, borosilicides, carborosilicides and nitrosilicides, a system shown in Figure 3 comprises an optional slurry production reactor in upstream of and in fluid communication with a hydrogen generation reactor. The slurry production reactor regenerates a metal hydride slurry that is utilized to produce hydrogen in the hydrogen generation reactor. At least a portion of the metal hydride in the hydrogen generation reactor is oxidized to a metal hydroxide during the recovery of hydrogen from the light metal hydrides. The hydrogen generation reactor utilizes electromagnetic radiation, convectional heating, PEM fuel cell exhaust, and the like to heat the hydride for the generation of hydrogen. The hydrogen generation reactor is also upstream of and in fluid communication with an optional drying and separation reactor and the metal hydroxide is transferred to the drying and separation reactor. At least a portion of metal hydroxide generated in the hydrogen generation reactor is recycled to the drying and separation reactor. The hydrogen generation reactor is optionally supplied with water. The optional drying and separation reactor separates any reusable fluids such as water from the metal hydroxides and recycles the fluid to the optional slurry production reactor. The system also comprises a

hydride recycle reactor in fluid communication with and downstream of the drying and separation reactor. Dry metal hydroxide from the drying and separation reactor is regenerated into a metal hydride in the hydride recycle reactor by contacting it with a mixture of gases comprising hydrogen. The hydride recycle reactor is supplied with carbon and oxygen in amounts effective to regenerate the metal hydride. The regenerated metal hydride is then recycled to the slurry production reactor for mixing with the recycled carrier liquids.

[0044] While the invention has been described with reference to exemplary embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted for elements thereof without departing from the scope of the invention. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the invention without departing from the essential scope thereof. Therefore, it is intended that the invention not be limited to the particular embodiment disclosed as the best mode contemplated for carrying out this invention, but that the invention will include all embodiments falling within the scope of the appended claims.

[0045] What is claimed is: